Simulating Surfzone Bubbles

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LONG TERM GOALS

Our long term goal is to develop a tested model of optical properties in the surf zone and adjacent nearshore ocean, including the influence of suspended sediment, bubble population and surface foam, to assess how optical properties are related to short term events such as individual breaking wave crests, and to determine how wave-driven surf zone circulation influences spatial distribution of optical properties just offshore of breaking through seaward transport of fine sediment, small persistent bubbles and surface foam.

OBJECTIVES

The ability to make optically-based observations in nearshore waters is strongly influenced by the presence of suspended sediment particles and of bubbles, both of which are present due to the action of breaking waves. Wave breaking is instrumental in injecting large volumes of air into the water column. This air volume subsequently evolves into a distribution of bubble sizes which interact with the fluid turbulence and are advected by the organized flow. Degassing of the water column can additionally generate a persistent foam layer which can prevent any optical penetration of the water column.

Our goal is to develop time-resolved models for these processes in order to make predictions of optical properties of the water column. To date, we have begun this process by incorporating a continuum description of bubble populations and associated dynamics in 2-D (Ripple) and 3-D (Truchas) Navier-Stokes solvers. In the continuation of this work, our objectives are to:

1) Implement a physics-based process model for bubble entrainment by small scale surface deformation processes, appropriate for application to established surf zone bores.

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2) Continue implementation of the multiphase model terms for bubble/bubble interactions.

3) Tackle the fluid mechanics problems associated with moving discretely resolved air volumes out of the model air phase and into the continuum bubble phases.

4) Develop a model for generation, transport and decay of a foam layer at the water surface.

APPROACH

Our approach to the problem has followed along two tracks: (1) incorporation of a comprehensive model of bubble physics within a 3D LES hydrodynamic code., for application in detailed process studies and development of parameterizations for use at larger scale, and (2) development of a model with lower resolution but retaining a fully 3-D structure, for use in sur zone simulations at spatial scales on the order of a kilometer or so. The physics is represented by a multiphase continuum model, using the formalism described by Drew and Passman (1999), with the details of a formulation for an air and water mixture found in Carrica et al (1999). In the present project, we have implemented a model combining a water phase, a bubble phase with multiple bubble size (or, more accurately, mass) bins. The existing 3-D model Truchas has been extended to include Carrica et al.'s polydisperse multiphase model and an LES turbulence closure model, and has been tested against a number of detailed experimental data sets on flow field turbulence and coherent vortical structures (Ting, 2008; Ting and Nelson, 2011). The effects of three-dimensional obliquely descending eddies (Nadaoka et al., 1989) and downburst (Kubo and Sunamura, 2001) on bubble transport are being investigated using the 3-D multiphase model.

A framework for performing simulations of bubble fields and surface foam distributions at kilometer length scales is beingdeveloped based on a fully 3-D nonhydrostatic wave resolving model. This model will be extended to incorporate bubble phases, and will be coupled to a model for foam generation, transport and decay on the water surface.

WORK COMPLETED

Following on work completed in FY11, we have tested a full 3-D VOF model for polydisperse multiphase flow and have documented this work in a submitted manuscript (Ma et al, 2012b). This model is available for further application in the project.

Turning to the problem of providing more useful wave-resolved model predictions at full surf zone scale, we first developed a robust shock-capturing scheme based on the finite volume TVD approach. Initially, we planned to base the model development on a Boussinesq-type, depth-integrated formulation in which the information about void fraction distribution would be incorporated in functional form with dependence on initial conditions, vertical elevation and time since the initiation of breaking event. This approach let to the development of the Boussinesq code FUNWAVE-TVD (Shi et al, 2012) which provides a robust model of a range of surfzone processes including breaking and runup without application of additional filtering steps. During this stage of the work, we decided, however, to concentrate our effort on a fully three-dimensional model which would eliminate the need to impose the vertical structure of void fraction. This led to the development of the code NHWAVE (Ma et al, 2012a), which is a shock capturing, fully nonhydrostatic, wave resolving model in surface and terrain following sigma coordinates. Extension of this model in the context of this project is described below.

RESULTS

The capabilities of the detailed 3-D model have been tested through examination of model predictions of coherent structures in the flow field and comparison to available laboratory data, including Ting (2008) and Ting and Nelson (2011). Figure 1 shows a comparison of coherent structures identified by the method of Jeong and Hussain (1995) and corresponding void fraction contours, illustrating the predferred clustering of bubbles within vortex cores. Further results are described in the manuscript of Ma et al (2012b). Comparisons of 2-D and 3-D calculations, each with and without bubbles, show that turbulent coherent structures are instrumental in determining the vertical distribution of void fraction in the water column, while, in turn, bubbles act to suppress the level of turbulence in the water column through the stabilizing effect of the resulting density gradient. Results indicate, in particular, that the tendency for many early simulations of wave-induced turbulence (such as Lin and Liu,1998) to overpredict turbulence levels in comparison to data is actually eliminated with proper incorporation of the stabilizing effect of buoyancy resulting from the bubble void fraction. We are presently investigating the effect of bubbles on the turbulence field as well as the effect of the choice of LES closure on the prediction of turbulent flow in the context of the experiments of Rapp and Melville (1990). Figure 2 shows examples of modeled TKE fields using dynamic (left) and static (right) Smagorinsky schemes. Preliminary indications are that the dynamic scheme provides an improved description of the spatial structure of the turbulent flow field. Further results for this case will be presented at the AGU 2012 Fall Meeting by Derakhti et al (2012).

The numerical codes FUNWAVE-TVD (Shi et al, 2012) and NHWAVE (Ma et al, 2012a) have been published and are available as open source code for community use. FUNWAVE-TVD has not been extended yet for multi-phase effects, as it was decided during the year to concentrate this effort on the 3-D model NHWAVE. Ma et al (2012a) describe basic testing of NHWAVE as a surfzone model. The model has also been extended to incorporate the multiphase bubble model. At present, we are performing more extensive tests of the model's ability to predict circulation and bubble void fraction over complex topography (RCEX). Figure 3 provides an illustration of modeled void fraction below a breaking wave crest. Figure 4 shows a plot of circulation and spatial distribution of void fraction for modeled rips during normally incendent wave conditions at RCEX. The NHWAVE model is presently being coupled to a model for foam distribution and transport on the water surface: this effort is to be reported on at the 2012 AGU Fall Meeting (Shi et al, 2012b).

IMPACT/APPLICATIONS

The work proposed here would provide a general framework for modeling bubble distribution and foam coverage in the surf zone. The model framework for bubble population is intended to be general in nature and will be applied at a later date in more computationally intensive studies of processes in individual breaking wave crests in a wide range of water depths.

RELATED PROJECTS

Kirby is a co-PI in MURI effort entitled "Impact of oceanographic variability on acoustic communications". This effort involves the development of a model for spatial and temporal distribution of bubble population under a sea surface with whitecap coverage, for use in water depths in the 50 to 100m range. Models developed in the present study are being used in support of efforts to parameterize bubble distributions under individual whitecap events.

Development and testing of the FUNWAVE-TVD code benefitted from support for the NSF PO project “Rip Current Dynamics in a Complex Beach Environment” to the Naval Postgraduate School, University of Delaware, and University of Miami. The code NHWAVE developed in this study is being used in support of the NSF PO project “The dynamics of sediment-laden river plume and initial deposition off small mountainous rivers” (Hsu and Kirby, UD, and Geyer, WHOI).

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PROJECT-SUPPORTED JOURNAL PUBLICATIONS

(Grilli et al 2012a,b and Kirby et al 2012 benefitted in a significant way from project support in relation to the development of the new FUNWAVE-TVD code)

Grilli, S. T., Harris, J. C., Tajalibakhsh, T., Masterlark, T. L., Kyriakopoulus, C., Kirby, J. T. and Shi, F., 2012, “Numerical simulation of the 2011 Tohoku tsunami based on a new transient FEM co-seismic source: Comparison to far- and nearfield observations”, *Pure and Applied Geophysics*, doi:10.1007/s00024-012-0528-y.

Grilli, S. T., Harris, J. C., Tappin, D. R., Masterlark, T., Kirby, J. T., Shi, F. and Ma, G., 2012, ``A multisource origin for the Tohoku-oki 2011 tsunami: earthquake and seabed failure", submitted to *Nature Communications*, October.

Kirby, J. T., Shi, F., Tehranirad, B., Harris, J. C. and Grilli, S. T., 2012, “Dispersive tsunami waves in the ocean: model equations and sensitiveity to dispersion and Coriolis effects”, revised and resubmitted to *Ocean Modelling*, September.

Ma, G., Shi, F., and Kirby, J. T., 2011, A polydisperse two-fluid model for surfzone bubble simulation, *J. Geophys. Res.,* **116**, C05010, doi:10.1029/2010JC006667.

Ma, G., Shi, F. and Kirby, J. T., 2012a, "Shock-capturing non-hydrostatic model for fully dispersive surface wave processes", *Ocean Modelling*, **43-44**, 22-35.

Ma, G., Kirby, J. T. and Shi, F., 2012b, "Numerical study of turbulent coherent structures and bubble entrainment under surfzone breaking waves", submitted to *J. Fluid Mech.*, February.

Shi, F., Kirby, J. T., and Ma, G., 2010a, Modeling quiescent phase transport of air bubbles induced by breaking waves, *Ocean Modelling* , **35**, 105-117.

Shi, F., Kirby, J. T., Harris, J. C., Geiman, J. D. and Grilli, S. T., 2012, "A high-order adaptive time-stepping TVD solver for Boussinesq modeling of breaking waves and coastal inundation", *Ocean Modelling*, **43-44**, 36-51.

OTHER PROJECT-SUPPORTED PUBLICATIONS AND PRESENTATIONS

Derakhti, M., Ma, G., Kirby, J. T. and Shi, F., 2012, "Numerical study of coherent structures and fluid-bubble interactions under deep-water breaking waves", to be presented at *AGU Fall Meeting*, San Francisco, Dec 3-7.

Kirby, J. T., Shi, F. and Holman, R. A., 2010, "Models and observations of foam coverage and bubble content in the surf zone", Abstract OS43C-06 presented at *2010 Fall Meeting*, AGU, San Francisco, CA, Dec. 13-17.

Kirby, J. T., Ma, G., Derakhti, M. and Shi, F., 2012, "Turbulent coherent structures, mixing and bubble entrainment under surf zone breaking waves", *Workshop on Environmental and Extreme Multiphase Flows*, Gainesville, March 14-16.

Kirby, J. T., Ma, G., Derakhti, M. and Shi, F., 2012, "Numerical investigation of turbulent bubbly flow under breaking waves", *Proc. 33d Int. Conf. Coastal Engrng.*, Santander.

Ma, G., Shi, F. and Kirby, J. T., 2010a, A polydisperse two-fluid model for bubble plumes under breaking waves", *Proc. 7th Int. Conf. Multiphase Flow*, ICMF 2010, Tampa, FL, May 30-June 4.

Ma, G., Kirby, J. T and Shi, F., 2010, "Numerical study of large-scale turbulence and bubble entrainment under surfzone breaking waves", Abstract OS51B-1314 presented at *2010 Fall Meeting*, AGU, San Francisco, CA, Dec. 13-17.

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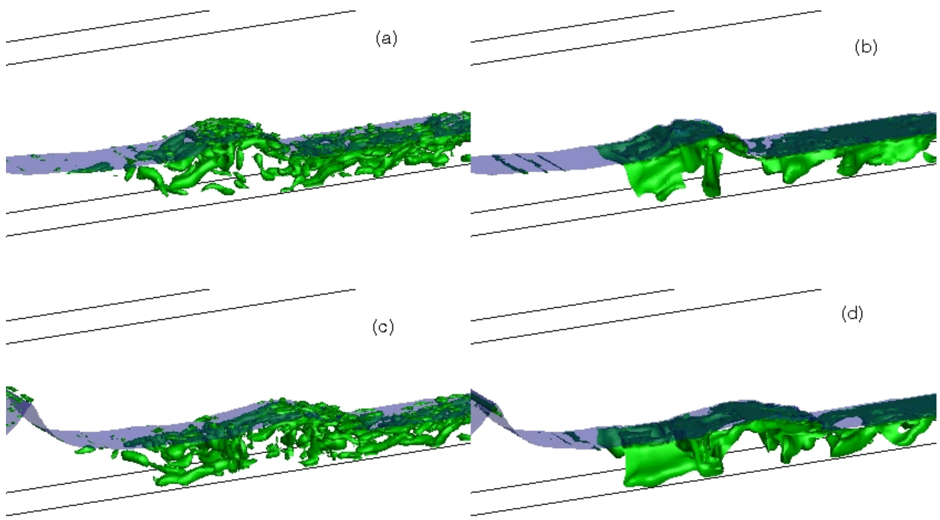

Figure 1. Example instantaneous vorticity (left) and void fraction (right) values showing the presence of obliquely descending eddy structures trailing behind wave crests and tilting more into the plain of the beach, with the eddies carrying entrained air more deeply into the water column (from Ma et al, 2012b).

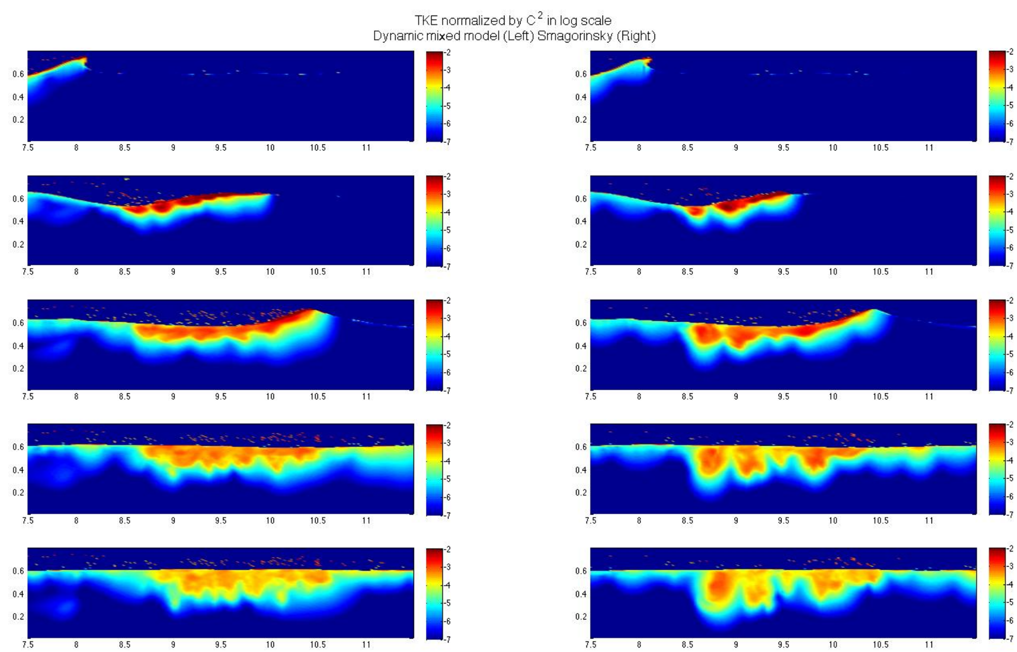

Figure 2. Simulated fields of TKE for experiment of Rapp and Melville (1990). Left panel: Dynamic Smagorinsky LES. Right panel: Static Smagorinsky LES.

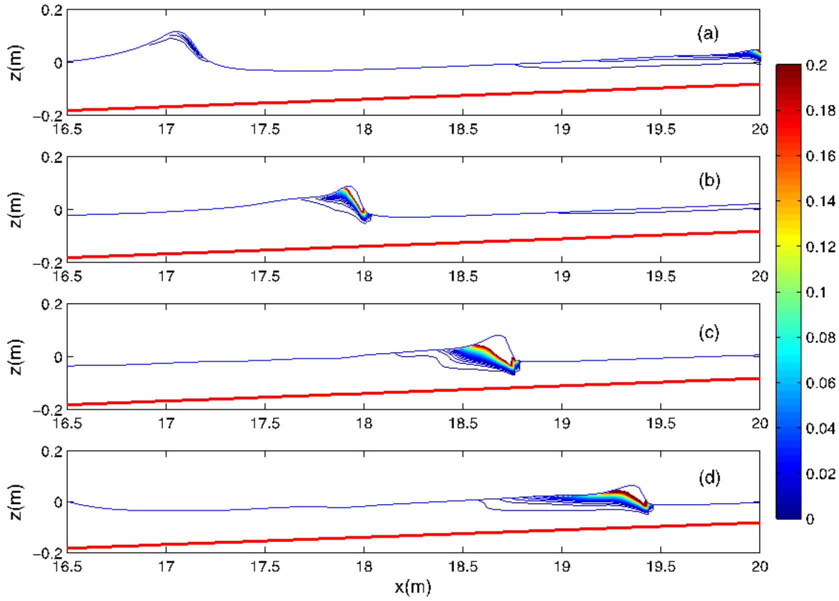

Figure 3. Void fraction distribution below progressive breaking wave crest in NHWAVE.

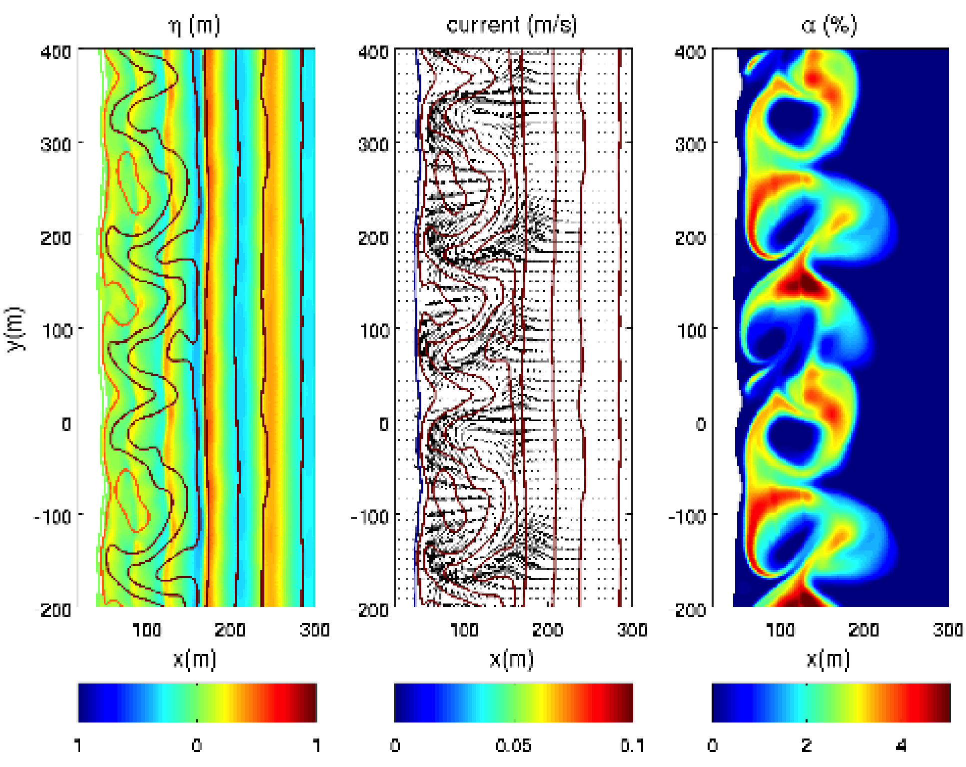

Figure 4: Rip current circulation cells over RCEX bathymetry for normally incident monochromatic waves. Left panel displays a snapshot of water surface elevsation and bathymetry contours. Center panel displays wave-averaged circulation in relation to bathymetry. The right panel displays depth-averaged void fraction (scale multiplied by 10).